

# Constraining Neutrino mass using the large scale HI distribution in the Post-reionization epoch

Ashis Kumar Pal<sup>\*</sup>, Tapomoy Guha Sarkar<sup>†</sup>

*Department of Physics, Birla Institute of Technology and Science, Pilani, Rajasthan, 333031, India.*

31 October 2016

## ABSTRACT

The neutral intergalactic medium in the post reionization epoch allows us to study cosmological structure formation through the observation of the redshifted 21 cm signal and the Lyman-alpha forest. We investigate the possibility of measuring the total neutrino mass through the suppression of power in the matter power spectrum. We investigate the possibility of measuring the neutrino mass through its imprint on the cross-correlation power spectrum of the 21-cm signal and the Lyman-alpha forest. We consider a radio-interferometric measurement of the 21 cm signal with a SKA1-mid like radio telescope and a BOSS like Lyman-alpha forest survey. A Fisher matrix analysis shows that at the fiducial redshift  $z = 2.5$ , a 10,000 hrs 21-cm observation distributed equally over 25 radio pointings and a Lyman-alpha forest survey with 30 quasars lines of sights in  $1\text{deg}^2$ , allows us to measure  $\Omega_\nu$  at a 3.25% level. A total of 25,000 hrs radio-interferometric observation distributed equally over 25 radio pointings and a Lyman-alpha survey with  $\bar{n} = 60\text{deg}^{-2}$  will allow  $\Omega_\nu$  to be measured at a 2.26% level. This corresponds to an idealized measurement of  $\sum m_\nu$  at the precision of  $(100 \pm 2.26)\text{meV}$  and  $f_\nu = \Omega_\nu/\Omega_m$  at 2.49% level.

**Key words:** cosmology: theory – large-scale structure of Universe - cosmology: diffuse radiation – cosmology: neutrino mass

## 1 INTRODUCTION

It has been established from neutrino oscillation experiments that neutrinos have mass. There are profound implications of these particles being massive and cosmological observations are expected to put strong constraints on neutrino physics. Several cosmological probes are used in this regard (Lesgourgues et al. 2013). We believe that at least two of the three species of neutrinos are non-relativistic today. Neutrinos are expected to be in thermal equilibrium with CMBR in the early Universe and their number is fixed. Accordingly their fractional contribution to the present day matter budget is given by  $f_\nu = \frac{\Omega_\nu}{\Omega_m}$  where  $\Omega_\nu = \sum_i m_i/93.14h^2\text{eV}$  (Lesgourgues & Pastor 2012, 2014) with  $m_i$  denoting the mass of each neutrino species. When the temperature of the universe is very high they can be treated as a part of radiation and after the CMB temperature drops below their masses, they can contribute to the matter density of the Universe. The free streaming behaviour of neutrinos causes them to wipe out fluctuations on scales smaller than the horizon scale when the neutrinos became non-relativistic (Hu & Eisenstein 1998; Eisenstein & Hu 1999; Lesgourgues et al. 2013). The free-streaming comoving vector is given by  $k_{fs} = \sqrt{3/2}H(z)/v(1+z)$  where  $v$  denotes the free-streaming speed. When neutrinos are relativistic, this coincides with the hori-

zon scale, and when neutrinos become non-relativistic at  $z = z_{nr}$  (Agarwal & Feldman 2011) it becomes

$$k_{nr} \sim \sqrt{\frac{3}{2}} \frac{H(z_{nr})m_\nu}{3T_\nu(z_{nr})(1+z_{nr})}.$$

For modes  $k < k_{nr}$  neutrinos behave like usual dark matter and there is no suppression of power. Modes with  $k > k_{fs}$  have neutrino perturbations wiped out and consequently CDM power spectrum is also suppressed. Cosmological measurement of neutrino mass (Croft et al. 1999a; Hannestad 2003; Pritchard & Pierpaoli 2008; Gratton et al. 2008; Vallinotto et al. 2009; Palanque-Delabrouille et al. 2015; Di Valentino et al. 2015; Giusarma et al. 2014; Allison et al. 2015; Chen et al. 2016) depends directly on the level of precision at which this suppression of power in the matter power spectrum can be detected. Whereas CMBR gives stringent constraints on neutrino mass (Lesgourgues et al. 2006; Oyama et al. 2013; Pan & Knox 2015; Planck Collaboration et al. 2014, 2015) it is necessary to obtain measurements from the low redshift Universe. Matter power spectrum for  $z < 1$  is highly non-linear and neutrino mass measurements have degeneracies with competition from dark energy (Hannestad 2005).

Mapping the neutral hydrogen distribution (HI) in the post-reionization epoch using the observation of the redshifted 21 cm signal towards measurement of the matter power spectrum has been studied as a means to measure neutrino mass (McQuinn et al. 2006a; Pritchard & Pierpaoli 2008; Oyama et al. 2013;

<sup>\*</sup> E-mail: ashispal475@gmail.com

<sup>†</sup> E-mail: tapomoy1@gmail.com

Shimabukuro et al. 2014; Liu et al. 2016; Oyama et al. 2016). At redshifts  $z < 6$ , HI responsible for the 21 cm signal lies predominantly in the Damped Lyman Alpha (DLA) clouds (Wolfe et al. 2005) and the diffuse collective 21 cm emission from these clouds form a background in radio observations. The redshifted 21-cm diffuse emission from the post-reionization epoch is well modelled using a constant neutral fraction (Storrie-Lombardi et al. 1996; P'eroux et al. 2003), and a bias function (Bagla et al. 2010; Guha Sarkar et al. 2012). The diffuse neutral gas distribution in the same redshift range can also be probed using the distinct absorption features of the Lyman-alpha forest (Rauch 1998). Large astrophysical foregrounds (Di Matteo et al. 2002; Santos et al. 2005; Gleser et al. 2008; Liu et al. 2009; Ghosh et al. 2011; Alonso et al. 2015) come in the way of detecting the 21 cm signal. The cross correlation of the 21 cm signal with other cosmological probes like the Lyman-alpha forest and Lyman-Break galaxies, has been proposed as a viable way (Guha Sarkar et al. 2011; Guha Sarkar & Datta 2015; Villaescusa-Navarro et al. 2015a) to mitigate the effect of foregrounds. The flux through the Lyman-alpha forest and the redshifted 21 cm signal can both be modeled as biased tracers of the underlying dark matter distribution and are expected to be correlated (McDonald 2003; Bagla et al. 2010; Guha Sarkar et al. 2012; Villaescusa-Navarro et al. 2014). The cross-correlation signal is a direct probe of the matter power spectrum over a large redshift range in the post reionization epoch.

In this paper we investigate the constraints on total neutrino mass using the cross correlation of the Lyman-alpha forest and the 21-cm signal from the post reionization epoch. The suppression of power on scales  $k > k_{nr}$  allows us to constrain the neutrino mass. In this paper we constrain the parameters  $\Omega_m$  and  $\Omega_\nu$  using the cross-correlation signal. These are the only two free parameters in our analysis. The values of  $\Omega_\Lambda = 0.685$ ,  $\Omega_b h^2 = 0.02222$ ,  $h = 0.6731$ ,  $n_s = 0.9655$ ,  $\sigma_8 = 0.829$  are fixed to their fiducial values as obtained from (Planck Collaboration et al. (2015) Table 4: TT + lowP) for this analysis.  $\Omega_K$  varies but is not treated as a free independent parameter. We consider a future radio interferometric observation of the 21 cm using a telescope like SKA1-mid<sup>1</sup> and a BOSS<sup>2</sup> like Lyman-alpha forest survey for obtaining predictions for bounds on the parameters.

## 2 CROSS CORRELATION SIGNAL AND ESTIMATION OF NEUTRINO MASS

The cross-correlation of the redshifted 21-cm signal and the transmitted flux through the Lyman-alpha forest has been proposed and studied as a cosmological probe of structure formation and background evolution in the post-reionization epoch (Guha Sarkar & Datta 2015). The two signals of interest owe their origins to neutral hydrogen (HI) in distinct astrophysical systems at redshifts  $z \leq 6$  but are expected to be correlated on large scales.

Bulk of the HI in the post-reionization epoch is believed to be housed in the dense self-shielded DLA systems. These clumps are the dominant source of the 21-cm emission in this epoch. The signal from individual DLA sources is rather weak and resolving individual sources is also rather unfeasible. The collective emission from the clouds, however form a diffuse background in all radio observations at observing frequencies less than 1420 MHz. Tomographic imaging using the low resolution intensity mapping of this

diffuse background radiation is a potentially rich probe of cosmology (Bharadwaj & Sethi 2001; Loeb & Wyithe 2008; Chang et al. 2008; Wyithe 2008; Bharadwaj et al. 2009; Wyithe & Loeb 2009; Camera et al. 2013; Bull et al. 2015).

Along a line of sight  $\hat{n}$  traversing a HI cloud at redshift  $z$  the CMBR brightness temperature changes from  $T_\gamma$  to  $T(\tau_{21})$  owing to the emission/absorption corresponding to the spin flip Hyperfine transition at  $\nu_e = 1420$  MHz in the rest frame of the gas.

$$T(\tau_{21}) = T_\gamma e^{-\tau_{21}} + T_s(1 - e^{-\tau_{21}}) \quad (1)$$

where  $\tau_{21}$  is the 21-cm optical depth and  $T_s$  is the spin temperature (Furlanetto et al. 2006). The quantity of interest in radio observations at a frequency  $\nu = \nu_e/(1+z)$  is the excess brightness temperature  $T_b(\hat{n}, z)$  redshifted to the observer at present. This is given by

$$T_b(\hat{n}, z) = \frac{T(\tau_{21}) - T_\gamma}{1+z} \approx \frac{(T_s - T_\gamma)\tau_{21}}{1+z}. \quad (2)$$

Writing  $\mathbf{r} \equiv (r\hat{n}, z)$ , where  $r$  is the comoving distance corresponding to  $z$ , we have the fluctuations in  $T_b(\hat{n}, z)$  given by  $\delta_T(\mathbf{r}) = \bar{T}(z) \times \eta_{HI}(\mathbf{r})$  (Bharadwaj & Ali 2004), where

$$\bar{T}(z) = 4.0\text{mK}(1+z)^2 \left( \frac{\Omega_{b0}h^2}{0.02} \right) \left( \frac{0.7}{h} \right) \left( \frac{H_0}{H(z)} \right) \quad (3)$$

and

$$\eta_{HI}(r\hat{n}, z) = \bar{x}_{HI}(z) \left\{ \left( 1 - \frac{T_\gamma}{T_s} \right) \left[ \delta_H(z, \hat{n}) - \frac{1+z}{H(z)} \frac{\partial v}{\partial r} \right] + \frac{T_\gamma}{T_s} s \delta_H(\hat{n}r, z) \right\} \quad (4)$$

Here  $\bar{x}_{HI}(z)$  denote the mean neutral fraction,  $\delta_H(z, \hat{n})$  denotes the HI density fluctuations and  $s$  is a function that takes into account the fluctuations of the spin temperature assuming it to be related to the HI fluctuations. The peculiar velocity of the gas,  $v$  introduces the anisotropic term  $(1+z)/H(z) \frac{\partial v}{\partial r}$ .

In the post reionization epoch one has  $T_\gamma/T_s \ll 1$  whereby the 21 cm signal is seen in emission and we have

$$\eta_{HI}(r\hat{n}, z) = \bar{x}_{HI}(z) \left[ \delta_H(z, \hat{n}) - \frac{1+z}{H(z)} \frac{\partial v}{\partial r} \right]. \quad (5)$$

In Fourier space the fluctuation in 21-cm excess brightness temperature  $\delta_T(\mathbf{r})$  is denoted by  $\Delta_T(\mathbf{k})$  and is given by

$$\Delta_T(\mathbf{k}) = C_T[1 + \beta_T \mu^2] \Delta(\mathbf{k}) \quad (6)$$

where  $\Delta(\mathbf{k})$  is the Fourier transform of the dark matter over density  $\delta$  and we have assumed that the peculiar velocity is sourced by dark matter over density. The quantity  $\beta_T$  is similar to the redshift space distortion (Hamilton 1998) parameter and  $\mu = \hat{n} \cdot \hat{\mathbf{k}}$ . The redshift dependent quantity  $C_T$  is given by  $C_T = \bar{T}(z)\bar{x}_{HI}(z)b_T$  where  $b_T$  denotes a bias that relates the HI fluctuations in Fourier space  $\Delta_H(\mathbf{k})$  to the underlying dark matter fluctuations  $\Delta(\mathbf{k})$  as  $\Delta_H(\mathbf{k}) = b_T \Delta(\mathbf{k})$ . The 21 cm bias has been studied in several independent studies (Khandai et al. 2009; Marín et al. 2010; Guha Sarkar et al. 2012). The small scale fluctuations clearly have a scale dependent bias which grows monotonically with  $k$ . There is also some additional scale dependence owing to fluctuations in the ionizing background (Wyithe & Loeb 2009). Numerical simulations show that on large scales the bias is however found to be a constant increasing only with redshift (Khandai et al. 2009; Marín et al. 2010; Guha Sarkar et al. 2012). We adopt a linear bias model (Guha

<sup>1</sup> <https://www.skatelescope.org/>

<sup>2</sup> <https://www.sdss3.org/surveys/booss.php>

Sarkar et al. 2012) in this work. It is important to note that in cosmologies with massive neutrinos HI is more clustered. This is an additional effect which occurs because we fundamentally believe that the gas is contained in halos and halos are rarer in models with neutrino mass and are thereby more biased (Massara et al. 2015). This enhances the 21-cm power spectrum by a roughly scale independent factor of 1.15 at  $z = 2.5$  (Villaescusa-Navarro et al. 2015b).

Whereas the dense clumpy HI sources the 21 cm emission, the diffuse intergalactic HI in the post reionization epoch also produces distinct absorption lines in the spectra of background quasars namely the Lyman-alpha forest (Hui & Gnedin 1997; Kim et al. 2007). The 21 cm signal and the Lyman-alpha forest arises from two distinct astrophysical systems. Bulk of the 21 cm emission comes from the dense HI clouds which are self shielded from the ionizing photons. The Lyman-alpha forest, on the other hand consists of absorption lines in the Quasar spectra which originates from tiny fluctuations in the low density diffuse HI along the line of sight. The Flux  $\mathcal{F}$  through the Lyman-alpha forest is modeled using the fluctuating Gunn-Peterson approximation (Gunn & Peterson 1965; Bi & Davidsen 1997)

$$\frac{\mathcal{F}}{\bar{\mathcal{F}}} = \exp^{-A(1+\delta)^\alpha} \quad (7)$$

where  $\alpha$  is related to the slope of the temperature density relationship  $\gamma$  as  $\alpha = 2 - 0.7(\gamma - 1)$ , and  $A$  (Kim et al. 2007) is a redshift dependent parameter depending on several astrophysical and cosmological parameters like the photo-ionization rate, IGM temperature and the evolution history (Croft et al. 1998, 1999b). The relationship between the observed flux through the Lyman-alpha forest and the underlying dark matter distribution is non-linear (Slosar et al. 2011). However, on large scales the smoothed Lyman-alpha forest flux traces the dark matter fluctuations (Viel et al. 2002; Saitta et al. 2008; Slosar et al. 2009) via a bias. The precise analytic understanding about the bias is not very robust and has been studied under certain approximations. However, a linear bias model is largely supported by numerical simulations of the Lyman-alpha forest (McDonald 2003).

The fluctuations of the flux through the Lyman-alpha forest  $\Delta_{\mathcal{F}}$  can hence be related to the dark matter fluctuations in Fourier space as

$$\Delta_{\mathcal{F}}(\mathbf{k}) = C_{\mathcal{F}}[1 + \beta_{\mathcal{F}}\mu^2]\Delta(\mathbf{k}) \quad (8)$$

The parameters  $(C_{\mathcal{F}}, \beta_{\mathcal{F}})$  are independent of one another and depend on  $A$ ,  $\gamma$  and the flux probability distribution function. The predictions for  $\beta_{\mathcal{F}}$  from particle-mesh simulations indicate that increasing the smoothing length has the effect of lowering the value of  $\beta_{\mathcal{F}}$  which is ideally set by choosing the smoothing scale at the Jean's length which is in turn sensitive to the IGM temperature. We adopt the values  $(C_{\mathcal{F}}, \beta_{\mathcal{F}}) = (-0.15, 1.11)$  from simulations of Lyman-alpha forest (McDonald 2003).

Being tracers of the underlying dark matter distribution the Lyman-alpha forest and 21 cm signal are expected to be correlated. The cross correlation of the Lyman-alpha forest and the 21cm signal has been proposed as a cosmological probe (Guha Sarkar et al. 2011; Guha Sarkar & Datta 2015). Apart from mitigating the serious issue of 21 cm foregrounds, the cross correlation if detected, ascertains the cosmological origin of the signal as opposed to the auto correlation 21 cm signal. Several advantages of the cross-correlation have been studied in earlier works (Guha Sarkar & Datta 2015). The 3D cross correlation power spectrum is defined

through

$$\langle \Delta_{\mathcal{F}}(\mathbf{k}) \Delta_T^*(\mathbf{k}') \rangle = (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}') P_{\mathcal{F}T}(\mathbf{k}), \quad (9)$$

with

$$P_{\mathcal{F}T}(\mathbf{k}) = C_{\mathcal{F}} C_T (1 + \beta_{\mathcal{F}}\mu^2)(1 + \beta_T\mu^2) P(\mathbf{k}). \quad (10)$$

where  $P(\mathbf{k})$  is the dark matter power spectrum.

Observationally the Lyman-alpha forest survey as well as radio observations of the 21 cm signal will probe certain volumes of the Universe. The cross-correlation can however be computed only in the overlapping region denoted by  $\mathcal{V}$ . The Lyman-alpha surveys typically shall cover a larger volume and thus  $\mathcal{V}$  is set by the 21-cm observations. If  $B$  be the observational bandwidth of the 21 cm observation and if  $\theta_a \times \theta_a$  is the angular patch that the radio telescope probes, then  $\mathcal{V} = B \frac{dr}{d\nu} \times r^2 \theta_a^2$ .

The observed 21 cm signal denoted by  $\Delta_{TO}$  shall include a noise term and may be written as

$$\Delta_{TO}(\mathbf{k}) = \Delta_T(\mathbf{k}) + \Delta_{NT}(\mathbf{k}) \quad (11)$$

Similarly the observed Lyman-alpha forest transmitted flux fluctuation in Fourier space may be written as

$$\Delta_{\mathcal{F}o}(\mathbf{k}) = \int \tilde{\rho}(\mathbf{k} - \mathbf{K}) \Delta_{\mathcal{F}}(\mathbf{K}) d^3\mathbf{K} + \Delta_{N\mathcal{F}}(\mathbf{k}) \quad (12)$$

which involves a convolution of the three dimensional field with a normalized sampling function in Fourier space  $\tilde{\rho}(\mathbf{k})$ , and  $\Delta_{N\mathcal{F}}(\mathbf{k})$  denotes a pixel noise contribution. The sampling function relates the one dimensional Lyman-alpha forest skewers to the 3D field and is given by

$$\rho(\mathbf{r}) = \frac{1}{N} \sum_i w_i \delta_D^2(\mathbf{r}_{\perp} - \mathbf{r}_{\perp i}) \quad (13)$$

with a set of weight functions  $w_i$  that are used to maximize the SNR and  $N$  is used to normalize  $\int \rho(\mathbf{r}) d^3\mathbf{r} = 1$ . The sum extends over all the QSO locations  $\mathbf{r}_{\perp i}$  in the field. The error in measurement of the cross power spectrum is hence given by  $\delta P_{\mathcal{F}T}(\mathbf{k})^2 = \sigma_{\mathcal{F}T}^2 / N_m$ , where

$$\sigma_{\mathcal{F}T}^2 = \frac{1}{2} \left[ P_{\mathcal{F}T}^2(\mathbf{k}) + \left( P_{\mathcal{F}\mathcal{F}}(\mathbf{k}) + P_{\mathcal{F}\mathcal{F}}^{1D}(k_{\parallel}) P_w^{2D} + N_{\mathcal{F}} \right) (P_{TT}(\mathbf{k}) + N_T) \right] \quad (14)$$

where  $P_{\mathcal{F}\mathcal{F}}^{1D}(k_{\parallel})$  denotes the one dimensional power spectrum of Lyman-alpha forest flux fluctuations

$$P_{\mathcal{F}\mathcal{F}}^{1D}(k_{\parallel}) = \frac{1}{(2\pi)^2} \int d^2\mathbf{k}_{\perp} P_{\mathcal{F}\mathcal{F}}(\mathbf{k}). \quad (15)$$

Here  $N_T$  and  $N_{\mathcal{F}}$  denotes the noise power spectrum for 21 cm observation and the Lyman-alpha forest respectively and  $P_w^{2D}$  denotes the power spectrum of the weight functions. The quantity  $N_m$  is the number of available Fourier modes and is given by

$$N_m(k, \mu) = \frac{2\pi k^2 \mathcal{V} dk d\mu}{(2\pi)^3}. \quad (16)$$

The noise power spectrum for the 21 cm observations and the Lyman-alpha forest depend on the specific observational parameters. For radio-interferometric observation of the 21 cm signal the noise power spectrum is a function of the mode  $k$  being probed and the observation frequency  $\nu = 1420 \text{ MHz}/(1+z)$  and is given by (McQuinn et al. 2006b; Wyithe et al. 2008)

$$N_T(k, \nu) = \frac{T_{sys}^2}{t_0} \left( \frac{c^2}{\nu^2 A_e} \right)^2 \frac{2r^2}{N_{ant}(N_{ant} - 1) f_{2D}(U, \nu)} \frac{dr}{d\nu}. \quad (17)$$

where,  $A_e$  denotes the effective collecting area of a single antenna,  $\mathbf{U} = \mathbf{k}_\perp r/2\pi$  and  $t_o$  is the total observation time for a single pointing. The system temperature is denoted by  $T_{sys}$ . If  $N_{ant}$  denotes the total number of antennae and  $f_{2D}(U, \nu)$  (Datta et al. 2007; Geil et al. 2011; Villaescusa-Navarro et al. 2015a) is the normalized baseline distribution function.

For the Lyman-alpha forest observations, the noise power spectrum is given by (McQuinn & White 2011)

$$N_{\mathcal{F}} = \sigma_{\mathcal{F}N}^2 / \bar{n} \quad (18)$$

where  $\bar{n}$  is the average quasar number density in the field given by  $\bar{n} = N_Q / r^2 \theta_a^2$  for a total of  $N_Q$  QSO spectra in the field of view and  $\sigma_{\mathcal{F}N}^2$  is the variance of the pixel noise with

$$\sigma_{\mathcal{F}N}^2 = \frac{1}{N_Q} \sum \bar{\mathcal{F}}^{-2} [S/N]_{\Delta x}^{-2} \left( \frac{\Delta x}{1 \text{Mpc}} \right). \quad (19)$$

The signal to ratio  $S/N$  in a pixel of size  $\Delta x$ , with  $\Delta x$  matched to the frequency smoothing scale of the 21 cm observation is considered to be held at a constant average value of 3. To make error estimates for the two parameters  $\Omega_\nu$  and  $\Omega_m$  we use the  $2 \times 2$  Fisher matrix with elements

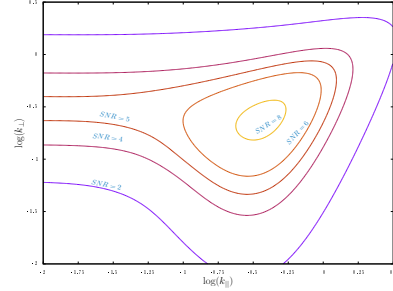
$$F_{rs} = \int \int \frac{1}{\sigma_{\mathcal{F}T}^2} \left( \frac{\partial P_{\mathcal{F}T}}{\partial \lambda_r} \right) \left( \frac{\partial P_{\mathcal{F}T}}{\partial \lambda_s} \right) \frac{2\pi k^2 \nu dk d\mu}{(2\pi)^3} \quad (20)$$

where  $\lambda_r$  and  $\lambda_s$  can take values  $\Omega_\nu$  and  $\Omega_m$ . The Cramer-Rao bound gives a limit on the theoretical errors on the  $i^{th}$  parameter as  $\delta\lambda_i = \sqrt{F_{ii}^{-1}}$  which we use in this paper.

### 3 RESULTS AND DISCUSSION

We have assumed a fiducial cosmological model with  $(\Omega_\Lambda, \Omega_m, h, n_s, \sum_i m_i) = (0.685, 0.315, 0.6731, 0.9655, 0.1 \text{eV})$  (Planck Collaboration et al. 2015) for this analysis. The fiducial redshift  $z = 2.5$  is chosen since the quasar distribution peaks in the redshift range  $2 < z < 3$ . At this fiducial redshift the Lyman-alpha forest spectrum can be measured in an approximate range  $\Delta z = 0.43$ . This is owing to the fact that part of the quasar spectrum  $\sim 10,000 \text{ Km s}^{-1}$  blue-ward of the Lyman-alpha emission and  $\sim 1000 \text{ Km s}^{-1}$  red-ward of the Ly- $\beta$  line has to be eliminated to avoid the quasar proximity effect and contamination from Ly- $\beta$  and other metal lines respectively. A high quasar density is required for the cross-correlation to be measured at high level of sensitivity. We consider a BOSS like Lyman-alpha forest survey with a quasar density of  $30 \text{ deg}^{-2}$  with an average  $3\sigma$  sensitivity for the measured spectra. The BOSS survey covers a large part of the sky with a transverse coverage of  $10,000 \text{ deg}^2$ . The volume probed by the Lyman-alpha forest is hence given by  $\frac{c}{H} \Delta z \times r^2 \theta^2$  with  $\Delta z = 0.43$  and  $\theta^2 = 3.043 \text{ rad}^2$ . We note, however that the cross-correlation can only be computed only in the overlapping volume between the Lyman-alpha forest survey and 21cm survey volume which is expected to be much smaller.

We consider an 21cm intensity mapping experiment using a radio interferometer with specifications roughly following that of SKA1-mid<sup>3</sup>. The radio interferometer shall operate in frequency range from 350 MHz to 14 GHz. The fiducial redshift of  $z = 2.5$  corresponds to a frequency of  $\sim 406 \text{ MHz}$  falls in this frequency range. We assume the array to be composed of a total of 250 dish



**Figure 1.** Signal to noise ratio for the cross-correlation power spectrum for a single pointing radio observation of 400 hrs. We have considered a QSO density  $30 \text{ deg}^{-2}$ .

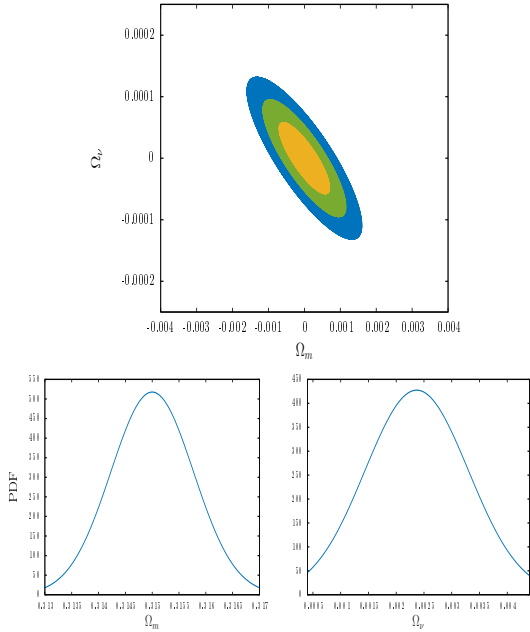
like antennae. Each individual antenna is of diameter  $\sim 15 \text{ m}$  with an antenna efficiency of 0.8. We assume that the distribution of the antennae is mostly condensed to a central core with 40%, 55%, 70%, and 100% of the total antennae are within 0.35 km, 1 km, 2.5 km, and 100 km radius respectively with density of antennae falling off radially as an inverse square power law (Villaescusa-Navarro et al. 2014). This allows us to compute the normalized baseline distribution function. It is evident that there can not be any baselines below 30m. Typical intensity mapping experiments aim towards higher power spectrum sensitivity at large scales. The telescope design supports this, since the telescopes are mostly distributed in a central region. The baseline coverage at very small non-linear scales is poor. We assume the system temperature  $T_{sys}$  to be 30K at observational frequency of 405.7MHz. Further, the telescope is assumed to have a 32MHz band width.

Figure (1) shows the signal to noise ratio for the cross-correlation signal in the  $(k_\perp, k_\parallel)$  plane. We have considered a 400 hrs observation of the 21-cm signal in a single pointing of the telescope. We find that a statistically significant detection of the cross-correlation signal at a  $\text{SNR} > 8$  is possible in the range  $0.19 \text{ Mpc}^{-1} < k_\parallel < 0.6 \text{ Mpc}^{-1}$  and  $0.18 \text{ Mpc}^{-1} < k_\perp < 0.36 \text{ Mpc}^{-1}$ . The anisotropy in the  $k$ -space owes its origin to the redshift space distortion effects and the preferential sensitivity of the noise in the  $k$ -space. We have assumed here that a perfect foreground subtraction has been achieved. Foreground residuals are expected to degrade the SNR. The issue of foreground removal has been discussed later. The low sensitivity at small baselines owes its origin to cosmic variance whereas the sensitivity at large scales is dictated by instrument noise.

We next, look at the results of the Fisher matrix analysis towards constraining the parameters  $(\Omega_m, \Omega_\nu)$ . Figure (2) shows the confidence ellipses at 68.3%, 95.4% and 99.8% levels. We have considered a total 10,000 hrs 21 cm observation for 25 pointings of radio telescope each corresponding to a 400 hrs observation. The Lyman-alpha forest survey is assumed to have QSO number density of  $30 \text{ deg}^{-2}$  where each spectrum is measured at an average  $> 3-\sigma$  pixel noise level. We find that for these observational parameters,  $\Omega_m$  and  $\Omega_\nu$  can be measured at 0.29% and 3.25% respectively. Figure (2) also shows the marginalized probability distribution for the parameters  $\Omega_m$  and  $\Omega_\nu$ . The SKA1-mid kind of radio interferometer considered here has a angular coverage of  $2.8 \times 2.8 \text{ deg}^2$  at redshift of 2.5. This is much smaller than volume covered by the Lyman-alpha survey. The BOSS Lyman-alpha survey covers a

<sup>3</sup> [http://www.skatelescope.org/wp-content/uploads/2012/07/SKA-TEL-SKO-DD-001-1\\_BaselineDesign1.pdf](http://www.skatelescope.org/wp-content/uploads/2012/07/SKA-TEL-SKO-DD-001-1_BaselineDesign1.pdf)





**Figure 2.** 68.3%, 95.4% and 99.8% ellipse for 10000 hrs. observations for 25 pointings with each pointing of 400 hrs. The marginalized one dimensional probability distribution function (PDF) for  $\Omega_m$  and  $\Omega_\nu$  are also shown.

Parameter	Fiducial value	% Error 25 pointings	% Error 50 pointings	% Error 100 pointings
$\Omega_m$	0.315	.361	0.280	0.222
$\Omega_m$	0.315	0.310	0.237	0.184
$\Omega_m$	0.315	0.298	0.227	0.176
$\Omega_m$	0.315	0.296	0.227	0.174
$\Omega_m$	0.315	0.292	0.222	0.171

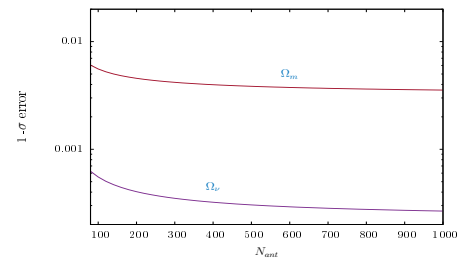
**Table 1.**  $1\sigma$  error for various number of pointings for  $\Omega_m$  with a total 10,000hrs observation of the 21 cm signal

much larger volume than a typical 21 cm observation. A significant part of the Lyman-alpha survey volume can be used in the cross-correlation by considering multiple pointings of the radio interferometer. We keep the total observation time fixed at 10,000 hrs but now consider 50 radio pointings each of 200 hrs duration. Further we consider the possibility of dividing the total observing time into 100 pointings. The results show a clear improvement in the constraints. We tabulate all the results in tables (1) and (2). This implies that for a QSO survey with a number density  $\bar{n} > 30 \text{ deg}^{-2}$  and with SKA like instrument, it is more advantageous to distribute the total observation time over as many fields of views as possible instead of deep imaging of a single radio field.

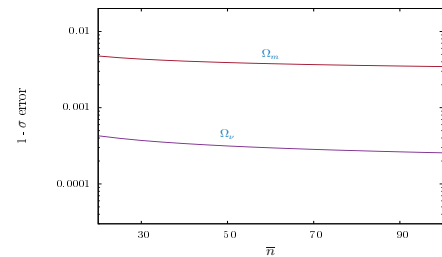
Up-to this point our analysis is focused on the estimates of the parameters HI 21 cm intensity mapping using (with SKA1-mid) and Lyman-alpha (BOSS) surveys, with some specific observational parameters (i.e, QSO density, number of antennae, and time of observations). In the next analysis our interest is focused on the variation of the error estimates if the above mentioned observa-

Parameter	Fiducial value	% Error 25 pointings	% Error 50 pointings	% Error 100 pointings
$\Omega_\nu$	$7.10 \times 10^{-4}$	20.70	16.53	13.81
$\Omega_\nu$	$1.42 \times 10^{-3}$	6.47	5.21	4.25
$\Omega_\nu$	$2.13 \times 10^{-3}$	3.73	3.00	2.45
$\Omega_\nu$	$2.37 \times 10^{-3}$	3.25	2.61	2.13
$\Omega_\nu$	$2.84 \times 10^{-3}$	2.57	2.07	1.68

**Table 2.**  $1-\sigma$  error for various number of pointings for  $\Omega_\nu$  with a total 10,000 hrs observation of the 21 cm signal.



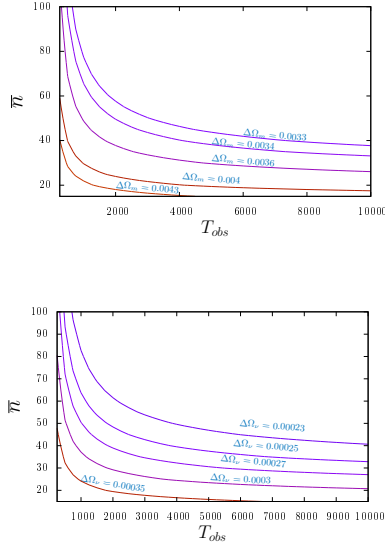
**Figure 3.** Variation of  $1-\sigma$  error of the parameters  $\Omega_m$  and  $\Omega_\nu$  with  $N_{ant}$  the number of antennas in the radio array.



**Figure 4.** Variation of  $1-\sigma$  error of the parameters  $\Omega_m$  and  $\Omega_\nu$  with  $\bar{n}$ .

tional parameters are changed within the known possible range. We first consider the effect of the variation of number of antennae from 100 to 1000 keeping the time of observation ( $t_0 = 400 \text{ hrs}$ ) and QSO density ( $\bar{n} = 30 \text{ deg}^{-2}$ ) unchanged. The total 10000 hrs time is hence divided over 25 radio pointings. The collecting area and resolution of the radio telescopes will increase with the number of antennae (keeping the dishes identical). Figure (3) shows the  $1-\sigma$  error bound on  $\Omega_m, \Omega_\nu$  varying with the number of antennas in the radio array. We find that there is no significant improvement in the constraints when number of antennas are increased beyond 350 and, the error bound saturates to a limit set by cosmic variance and the parameters of the Lyman-alpha survey. The noise contribution from the Lyman-alpha forest power spectrum measurement depends on the number density of Quasars in the survey. Figure (3) represents the improvement of  $1\sigma$  error in the estimation of parameters due to the of variation QSO density ( $\bar{n}$ ). In this case we find that beyond  $\bar{n} > 50$  the decline of the error is very slow and the cosmic variance limit is asymptotically reached.

For a more practical scenario it is useful to investigate the optimal observational strategy. We characterize the radio observation with the time of observation and Lyman-alpha forest survey with



**Figure 5.**  $\Omega_m$  and  $\Omega_\nu$  contours in the  $\bar{n}$  and time of observation plane.

the quasar number density in the survey with high SNR spectra. Figure (5) shows the contours of constant  $1\sigma$  errors of  $\Omega_m$ ,  $\Omega_\nu$  for a single pointing radio observation. The bottom left corresponds to large observational noise owing to small quasar number density and small time of observation. The top right corner corresponds to large quasar density and long duration radio observation. The error in the parameters show a decrease as one moves from the bottom left to the top right corner through the contours. However, beyond a point there is no further improvement and this corresponds to the cosmic variance limit. In this limit the parameter  $\Omega_m$  can be measured at a 0.9% level and  $\Omega_\nu$  can be measured at 7.6%. Further improvement is only possible through increase of the number of pointings which increases the survey volume and the errors scale as  $\sim 1/\sqrt{N_{\text{point}}}$ . A total of 25,000 hrs radio observation distributed equally over 25 pointings and a Lyman-alpha survey with  $\bar{n} = 60\text{deg}^{-2}$  will allow  $\Omega_\nu$  to be measured at a 2.26% level. This corresponds to a measurement of  $\sum m_\nu$  at the precision of  $(100 \pm 2.26)\text{meV}$  and  $f_\nu$  at 2.49%. Our general observation is that there should be greater emphasis of increasing survey volumes through bigger bandwidths or using smaller dishes and considering multiple fields of views against extremely deep surveys in small fields. This shall make the constraints parameters stronger. we however note that 25,000 hrs observation in 25 pointings is a rather unfeasible observational strategy. In this idealized survey it is possible to even look into the mass hierarchy for neutrinos. However, Several observational issues poses severe problems towards detection of the signal. The crucial issue as regarding the 21 cm signal, is the issue of foregrounds. Foregrounds like the galactic synchrotron radiation and extra galactic point sources are several orders of magnitude larger than the cosmological 21 cm signal. Further, man made RFIs (Ellingson 2005) also contaminate the signal severely. Several foreground subtraction methods have been proposed. We note that though foreground subtraction is crucial towards measuring the 21 cm signal, these contaminants appear as noise in the cross-correlation and foreground residuals even of the same order of magnitude as the signal shall not entirely inhibit the detection of the cross-correlation signal unlike the unlike the auto correlation.

Assuming a fiducial model with  $\sum m_\nu = 0.1\text{eV}$  we find that if we have a foreground residual of the 21-cm signal at 200% of the signal itself then the constraint on  $\Omega_\nu$  degrades from 2.26% to 2.7%. Further, if the Lyman- $\alpha$  forest pixel noise is at  $1 - \sigma$ , the constraint on neutrino mass degrades to  $\sim 6\%$ .

The Lyman-alpha forest surveys require very high SNR measurement of a large number of spectra for high precision detection of the cross-correlation signal which is necessary for obtaining stringent bounds on the neutrino mass. Further, one has to worry about several other observational issues like the effect of Galactic super wind, contamination from other metal lines etc. We conclude by noting that with future radio-observations of the cosmological redshifted 21-cm signal and Lyman-alpha forest surveys, it is possible to measure neutrino mass at a high level of precision using the cross-correlation power spectrum. We predict that the bounds obtained from such a measurement shall be competitive with other probes.

#### 4 ACKNOWLEDGEMENTS

TGS would like to acknowledge the Department of Science and Technology (DST), Government of India for providing financial support through the project SR/FTP/PS-172/2012.

#### REFERENCES

- Agarwal S., Feldman H. A., 2011, *MNRAS*, **410**, 1647
- Allison R., Caucal P., Calabrese E., Dunkley J., Louis T., 2015, *PRD*, **92**, 123535
- Alonso D., Bull P., Ferreira P. G., Santos M. G., 2015, *MNRAS*, **447**, 400
- Bagla J. S., Khandai N., Datta K. K., 2010, *MNRAS*, **407**, 567
- Bharadwaj S., Ali S. S., 2004, *MNRAS*, **352**, 142
- Bharadwaj S., Sethi S. K., 2001, *Journal of Astrophysics and Astronomy*, **22**, 293
- Bharadwaj S., Sethi S. K., Saini T. D., 2009, *PRD*, **79**, 083538
- Bi H., Davidsen A. F., 1997, *ApJ*, **479**, 523
- Bull P., Ferreira P. G., Patel P., Santos M. G., 2015, *ApJ*, **803**, 21
- Camera S., Santos M. G., Ferreira P. G., Ferramacho L., 2013, *Physical Review Letters*, **111**, 171302
- Chang T., Pen U., Peterson J. B., McDonald P., 2008, *Physical Review Letters*, **100**, 091303
- Chen Y., Ratra B., Biesiada M., Li S., Zhu Z.-H., 2016, preprint, ([arXiv:1603.07115](https://arxiv.org/abs/1603.07115))
- Croft R. A. C., Weinberg D. H., Katz N., Hernquist L., 1998, *ApJ*, **495**, 44
- Croft R. A. C., Hu W., Davé R., 1999a, *Physical Review Letters*, **83**, 1092
- Croft R. A. C., Weinberg D. H., Pettini M., Hernquist L., Katz N., 1999b, *ApJ*, **520**, 1
- Datta K. K., Choudhury T. R., Bharadwaj S., 2007, *MNRAS*, **378**, 119
- Di Matteo T., Perna R., Abel T., Rees M. J., 2002, *ApJ*, **564**, 576
- Di Valentino E., Giusarma E., Mena O., Melchiorri A., Silk J., 2015, preprint, ([arXiv:1511.00975](https://arxiv.org/abs/1511.00975))
- Eisenstein D. J., Hu W., 1999, *ApJ*, **511**, 5
- Ellingson S. W., 2005, in N. Kassim, M. Perez, W. Junor, & P. Henning ed., *Astronomical Society of the Pacific Conference Series Vol. 345*, Astronomical Society of the Pacific Conference Series. pp 321–332
- Furlanetto S. R., Oh S. P., Briggs F. H., 2006, *Physics Report*, **433**, 181
- Geil P. M., Gaensler B. M., Wyithe J. S. B., 2011, *MNRAS*, **418**, 516
- Ghosh A., Bharadwaj S., Ali S. S., Chengalur J. N., 2011, *MNRAS*, **418**, 2584
- Giusarma E., Di Valentino E., Lattanzi M., Melchiorri A., Mena O., 2014, *PRD*, **90**, 043507
- Gleser L., Nusser A., Benson A. J., 2008, *MNRAS*, **391**, 383
- Gratton S., Lewis A., Efstathiou G., 2008, *PRD*, **77**, 083507
- Guha Sarkar T., Datta K. K., 2015, *J. Cosmology Astropart. Phys.*, **8**, 001

- Guha Sarkar T., Bharadwaj S., Choudhury T. R., Datta K. K., 2011, *MNRAS*, **410**, 1130
- Guha Sarkar T., Mitra S., Majumdar S., Choudhury T. R., 2012, *MNRAS*, **421**, 3570
- Gunn J. E., Peterson B. A., 1965, *ApJ*, **142**, 1633
- Hamilton A. J. S., 1998, Kluwer Academic Publishers ASSL 231
- Hannestad S., 2003, *J. Cosmology Astropart. Phys.*, **5**, 004
- Hannestad S., 2005, *Phys. Rev. Lett.*
- Hu W., Eisenstein D. J., 1998, *ApJ*, **498**, 497
- Hui L., Gnedin N. Y., 1997, *MNRAS*, **292**, 27
- Khandai N., Datta K. K., Bagla J. S., 2009, preprint, ([arXiv:0908.3857](https://arxiv.org/abs/0908.3857))
- Kim T., Bolton J. S., Viel M., Haehnelt M. G., Carswell R. F., 2007, *MNRAS*, **382**, 1657
- Lesgourgues J., Pastor S., 2012, preprint, ([arXiv:1212.6154](https://arxiv.org/abs/1212.6154))
- Lesgourgues J., Pastor S., 2014, *New Journal of Physics*, **16**, 065002
- Lesgourgues J., Perotto L., Pastor S., Piat M., 2006, *PRD*, **73**, 045021
- Lesgourgues J., Mangano G., Miele G., Pastor S., 2013, *Neutrino Cosmology*. Cambridge University Press, <https://books.google.co.in/books?id=um6TyAv3pTwC>
- Liu A., Tegmark M., Bowman J., Hewitt J., Zaldarriaga M., 2009, *MNRAS*, **398**, 401
- Liu A., Pritchard J. R., Allison R., Parsons A. R., Seljak U., Sherwin B. D., 2016, *PRD*, **93**, 043013
- Loeb A., Wyithe J. S. B., 2008, *Physical Review Letters*, **100**, 161301
- Marín F. A., Gnedin N. Y., Seo H.-J., Vallinotto A., 2010, *ApJ*, **718**, 972
- Massara E., Villaescusa-Navarro F., Viel M., Sutter P. M., 2015, *J. Cosmology Astropart. Phys.*, **11**, 018
- McDonald P., 2003, *ApJ*, **585**, 34
- McQuinn M., White M., 2011, *MNRAS*, **415**, 2257
- McQuinn M., Zahn O., Zaldarriaga M., Hernquist L., Furlanetto S. R., 2006a, *ApJ*, **653**, 2
- McQuinn M., Zahn O., Zaldarriaga M., Hernquist L., Furlanetto S. R., 2006b, *ApJ*, **653**, 815
- Oyama Y., Shimizu A., Kohri K., 2013, *Physics Letters B*, **718**, 1186
- Oyama Y., Kohri K., Hazumi M., 2016, *J. Cosmology Astropart. Phys.*, **2**, 008
- Palanque-Delabrouille N., et al., 2015, *J. Cosmology Astropart. Phys.*, **2**, 045
- Pan Z., Knox L., 2015, *MNRAS*, **454**, 3200
- P'eroux C., McMahon R. G., Storrie-Lombardi L. J., Irwin M. J., 2003, *MNRAS*, **346**, 1103
- Planck Collaboration et al., 2014, *A&A*, **571**, A16
- Planck Collaboration et al., 2015, preprint, ([arXiv:1502.01589](https://arxiv.org/abs/1502.01589))
- Pritchard J. R., Pierpaoli E., 2008, *PRD*, **78**, 065009
- Rauch M., 1998, *Annual Review of Astronomy & Astrophysics*, **36**, 267
- Saitta F., D'Odorico V., Bruscoli M., Cristiani S., Monaco P., Viel M., 2008, *MNRAS*, **385**, 519
- Santos M. G., Cooray A., Knox L., 2005, *ApJ*, **625**, 575
- Shimabukuro H., Ichiki K., Inoue S., Yokoyama S., 2014, *PRD*, **90**, 083003
- Slosar A., Ho S., White M., Louis T., 2009, *Journal of Cosmology and Astro-Particle Physics*, **10**, 19
- Slosar A., Font-Ribera A., Pieri M. M. e. a., 2011, *J. Cosmology Astropart. Phys.*, **9**, 1
- Storrie-Lombardi L. J., McMahon R. G., Irwin M. J., 1996, *MNRAS*, **283**, L79
- Vallinotto A., Viel M., Das S., Spergel D. N., 2009, preprint, ([arXiv:0910.4125](https://arxiv.org/abs/0910.4125))
- Viel M., Matarrese S., Mo H. J., Haehnelt M. G., Theuns T., 2002, *MNRAS*, **329**, 848
- Villaescusa-Navarro F., Viel M., Datta K. K., Choudhury T. R., 2014, *J. Cosmology Astropart. Phys.*, **9**, 50
- Villaescusa-Navarro F., Viel M., Alonso D., Datta K. K., Bull P., Santos M. G., 2015a, *J. Cosmology Astropart. Phys.*, **3**, 034
- Villaescusa-Navarro F., Bull P., Viel M., 2015b, *ApJ*, **814**, 146
- Wolfe A. M., Gawiser E., Prochaska J. X., 2005, *ARA&A*, **43**, 861
- Wyithe J. S. B., 2008, *MNRAS*, **388**, 1889
- Wyithe J. S. B., Loeb A., 2009, *MNRAS*, **397**, 1926